

# Bistability double crossing curve effect in a polariton-laser semiconductor microcavity

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We report an experimental observation of polaritonic optical bistability of the laser emission in a planar semiconductor microcavity with a 100Å GaAs single quantum well in the strong-coupling regime. The bistability curves show crossings that indicate a competition between a Kerr-like effect induced by the polariton population and thermal effects. Associated with the bistability, laser-like emission occurs at the bare cavity mode.

Bistability is a very general phenomenon involving a phase transition far from thermal equilibrium. Since its first observation in a passive, unexcited sodium vapor medium[1], it has been observed in many different materials including tiny semiconductor etalons. In counterparts, many of the phenomena studied in lasers, such as fluctuations, regenerative pulsations, and optical turbulence, can be observed in passive bistable systems, often under better controlled conditions. Their applications are based in dispersive and temperature switching using optical bistability (OB) properties, suggesting possibilities in high-speed all-optical signal processing.

Generally an optical bistability (OB) event requires that both the input and the output are optical signals. In order to obtain OB, light and matter must be closely coupled together. The cavity field, which is enhanced by the resonance condition, depends strongly on the dielectric function of the medium inside the cavity producing the optical feedback. The sharpness of the exciton and cavity modes results in the strong coupling. This means that the exciton mode and the cavity photon mode are in such close interaction as to give rise to two polariton states resulting in an anti-crossing (Rabi-splitting) between the upper and lower polariton branches.

The scattering mechanism is marked by generation of two polaritons with wave-vectors  $\vec{k} = 0$  (signal) and  $\vec{k} = 2\vec{k}_p$  (idler), where  $\vec{k}_p$  is the excitation wave-vector, which can be controlled by the incidence angle and corresponds to the nontrivial solution for the energy conservation condition. In this case, we have a better optimization of this parametric amplification and a minimum in the parametric scattering threshold intensity. Thus, the “magic angle” is  $\theta_m = \arcsen(n_{qw}\sqrt{\Omega/\omega_{e-p}}) \approx 9^\circ \pm 2^\circ$ , for a  $\lambda$ -cavity containing a single quantum well like gain media with refractive index  $n_{qw}$ , Rabi-splitting energy of  $\hbar\Omega = 3.4meV$  and a exciton-polariton (e-p) peak emission in  $\omega_{e-p}$ .

The nonlinearities associated with the reduced normal mode splitting, while the excitation power is increased, produce a collapse of the polariton modes and the crossover between the strong and weak regimes[2, 3, 4]. These effects have been interpreted in terms of bleaching of the exciton absorption[2] and excitation induced dephasing[3] due to exciton-exciton interaction. There-

fore, all the nonlinear behavior would affect strongly the optical response of the microcavity in a resonant excitation condition. Thus, we report an experimental study of the optical nonlinearities of a normal mode in a semiconductor microcavity by means of laser emission, demonstrating the presence of a bistable response under resonant excitation conditions. We investigate the optical bistability providing a detuning between cavity-exciton and pump laser-exciton energies which play an important role in the nonlinear kinetics of microcavity polariton scattering as well.

Through this resonant excitation conditions, Ciuti *et al.* define an effective Hamiltonian[5] for polariton-polariton interaction analogous to the Hamiltonian for an optical Kerr medium. The difference here is the dependence of the refractive index on the polariton number instead of the photon number. This results in bistable behavior for high enough excitation intensities, as in the Kerr medium inside a cavity. OB has been observed in this manner in both the weak[6] and strong-coupling[7] regimes (under different conditions).

Moreover, due to a large variety of nonlinearities in microcavity normal modes, the pump power heats the sample proportionally to the increase of the absorption at resonance. This may results in a bistable behavior for high enough excitation intensities, as in a Kerr medium in a cavity, producing different kinds of OBs.

In a recent work[8], the dynamic equations for the polariton field and the bistability threshold were analyzed, as well as the reflectivity and transmission spectra, but still in steady-state regime. Following these theoretical results, we realize an experimental observation of the OB caused by changes in the refractive index due to a large e-p population in a semiconductor microcavity in the strong-coupling regime through e-p laser emission. The behavior of the bistable response, varying the “cw” pump energy as well as the cavity resonance, reveals singularities such as double crossings between the branches of the OB curve, which play an important role in the nonlinear kinetics of microcavity polariton scattering. An interpretation of the data is presented, but a detailed theoretical explanation of these observations is beyond the scope of this work.

The sample[9] was held in a cold-finger cryostat at a temperature of 10K. A tunable cw Ti:Sapphire laser line amplitude was modulated using an acousto-optic modulator (AOM) coupled to a digital function generator, producing a sinusoidal waveform pump at 1MHz (see fig.1-a).

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The lower-polariton branch (LPB) is excited resonantly using a right circularly polarized beam (heavy-hole excitons) through a  $\lambda/4$  plate in the pump laser path. The angle of incidence was controlled by shifting the pump laser laterally toward a lens, being fixed in  $12^\circ$  and focused to a  $40\mu\text{m}$  spot size. This same lens is used to collimate the light emitted by the sample within a broad cone concentrated within  $\pm 15^\circ$  due to the effect of the “polariton energy trap”, formed by the dispersion relation. The emission spectra are obtained using a spectrometer with a grating (1800 grooves/mm) and a cooled CCD. Detection of the pump and the e-p emission intensities were performed using two variable-gain photodetectors. For OB measurements, we calibrate the system splitting the input beam, where the collected signals are coupled to X-Y oscilloscope channels, and set the photodetector gains to achieve a straight line relation between them.

In our discussion we will consider only the signal emission, because it has a recombination probability much larger than idler emission, for the used incident angle. Experimentally, a scanned detection angle solved experiment around the  $\vec{k} = 2\vec{k}_p$  direction, with the pump energy maintained always resonant with the lower polariton branch, was realized. But, we did not observe the idler emission in these experimental conditions, same in the range of the detuning to the exciton-cavity and laser-exciton used in this paper.

Reflectance measurements (see fig.1-b) show a Rabi interaction frequency between excitons and photons of  $\hbar\Omega \equiv [g^2 - (\gamma - \kappa)^2/4]^{1/2} \approx 3.4\text{meV}$ , where  $g$  is the rate at which the excitons are coupled with the cavity field,  $\kappa$  is the decay rate of the cavity field and  $\gamma$  is the spontaneous emission rate. The resonance condition was obtained with a detuning between the emission of the e-p mode and the cavity mode as  $\Delta_c = E_{cav} - E_{e-p} = -0.2\text{meV}$ . The detuning between the pump laser and the e-p lower polariton laser was  $\Delta_L = E_{e-p} - E_L = -3.7\text{meV}$ .

Fig. 1-c shows a sequence of emission spectra pointing the repulsive polariton-polariton interaction, manifesting itself a phase-space filling effect (as first noted in Ref.[13]), leading to bleaching of the excitonic oscillator strength and a blue-shift of the exciton resonance. The maximum blue shift of  $0.4\text{meV}$  is still much less than half of the UP-LP splitting of  $3.4\text{meV}$ ; i.e., the energy of the emission always remains distinctly below the QW exciton and cavity photon energies. This ensures that the polariton is still the normal mode of the system.

Using the theoretical results discussed in Ref.[8] and  $a_{exc} = 100\text{\AA}$  (for 2D Bohr radius of the exciton in GaAs[10]) we obtain the theoretical OB curve shown in fig.2, and the bistability condition:  $\Delta_L < -\sqrt{3}\Gamma_{e-p} = -1.3\text{meV}$ , where  $\Gamma_{e-p}$  is the exciton-polariton linewidth obtained from cavity ( $\Gamma_c$ ), exciton ( $\Gamma_{exc}$ ) linewidths and the Hopfield coefficients[11]. In our sample, the cavity quality factor  $Q = E_c/\Gamma_c = 1.5533\text{eV}/1.04\text{meV} \approx 1500$  and  $\Gamma_{exc} = 0.11\text{meV}$ , resulting  $\Gamma_{e-p} = 0.75\text{meV}$ .

A theoretical analysis shows that  $n_p^+ \approx 2.8n_p^-$  and  $P^- \approx 4P^+$ , where  $n_p^\pm$  and  $P^\pm$  (defined in the fig.2)

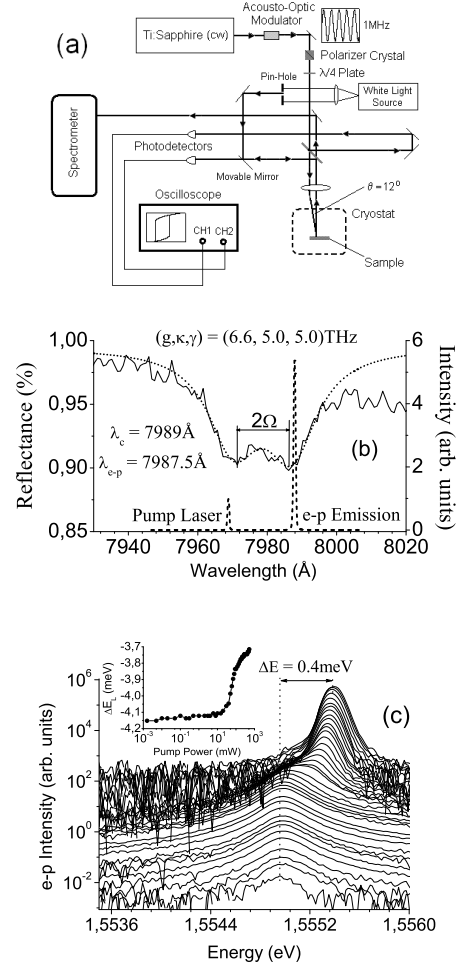


FIG. 1: (a) Experimental Setup scheme. (b) The solid line (left axis) is a photoreflectance measurement using white light. The dotted line is a fit using strong-coupling model[14] ( $\lambda_c$  is the resonance cavity wavelength,  $\lambda_{e-p}$  is the exciton-polariton peak emission). The dashed curve (right axis) is a resonant photoluminescence measurement that shows the exciton-polariton laser emission and the laser pump. (c) Resonant photoluminescence measurement for several pump powers (from 1mW at 500mW). Inset: The behavior for the blue-shift of the e-p emission (relative peak position  $\Delta E = E_{e-p} - E_L$ , where  $E_L = 1.5513\text{eV}$ ) vs pump power.

are respectively the threshold for mean polariton number and pump power to the bistability forward (−) and turning (+) points. The minimum exciton-laser detuning and its respective pump power threshold is obtained when  $\Delta_L^{min} = -\sqrt{3}\Gamma_{e-p} = -1.3\text{meV}$ . With this condition, we find the minimum cavity detuning  $\Delta_c^{min} = [\hbar\Omega(2\Gamma_c - \Gamma_{exc})/(2\sqrt{2}\Gamma_c\Gamma_{exc})] = -2.4\text{meV}$  (using the mentioned parameters).

Thus, the model predicts a dispersive OB due to e-p population in our sample, but these theoretical results, and an analysis of the threshold equations for cavity-exciton and exciton-laser detuning using ref.[8] do not foresee a crossing effect between the branches in the OB curve.

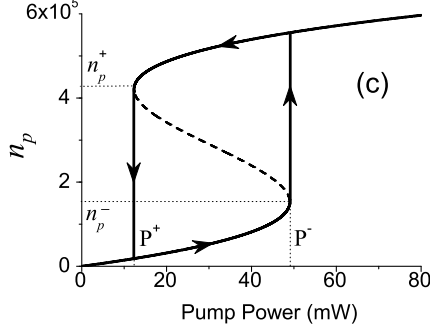


FIG. 2: The mean number of polaritons  $n_p$  vs the pump power  $P_{in}$ . The dashed line shows the unstable region. The arrows indicate the hysteresis cycle obtained by scanning the input power in both directions.

Experimental results for the OB are shown in fig.3 for different excitation energies, where one can see two crossings between the turn-on and the turn-off curves for  $\Delta_L = -3.10\text{meV}$ . The bistable behaviors can be of dispersive or absorptive nature, or a competition between both. Moreover, since thermal conduction plays an important role in the dynamics of thermal optical bistable devices, an expression for the thermal conduction time is useful. If a laser beam suddenly heats a cylinder of length much smaller than the beam radius  $r_o$ , the heat diffusion equation leads to a thermal conduction time of[18]

$$\tau_{th} = \frac{c_v \rho r_o^2}{(2.4)^2 K_c} \quad (1)$$

where  $c_v$  is the specific heat,  $\rho$  is the density, and  $K_c$  is the thermal conductivity.  $K_c$  and  $c_v$  both depend upon temperature, so that  $\tau_{th}$  can change by several orders of magnitude. Also,  $\tau_{th}$  is proportional to the square of the pump laser beam radius; small dimensions can result in short conduction times. For GaAs at 10K,  $c_v = 2.7\text{J}/(\text{kg}\cdot\text{K})$ [15],  $K_c = 1400\text{W}/(\text{m}\cdot\text{K})$ ,  $\rho = 5316.5\text{kg}/\text{m}^3$  (see Ref.[16]) leading to  $\tau_{th} \approx 712\text{ps}$ . For a modulated pumping frequency of 1MHz we have an quasi steady-state, in which the input is turned on and off through sinusoidal pulses with duration much larger than  $\tau_{th}$ , but shorter than the time to reach complete thermal equilibrium with the surroundings. Thus, the system can show an overshoot in the switch-on for  $n_p$ , soon after the input reaches it is maximum. Although the input is reduced as quickly as it is increased, we also see an overshoot in switching off for the cooling operation.

For thermal bistability, the effective pump power per pass that excites the gain medium in the laser cavity is:  $P_p = P_o T R \times (1 - L_i)^2 \times (1 - \exp[-\alpha_c L_c])^2 \times \exp[-2\alpha_{qw} L_{qw}] = 16\text{mW}$ , where  $P_o = 240\text{mW}$  is the pump power at the sample surface,  $\alpha_{c(qw)} = 13267\text{cm}^{-1}(1.5 \times 10^5\text{cm}^{-1})$  is the optical absorption coefficient of  $\text{GaAs}(\text{Al}_{0.3}\text{Ga}_{0.7}\text{As})$  (at 10K and excited resonantly)[15],  $L_i$  is internal cavity loss, where  $L_i = \gamma\tau_i$  ( $\gamma$  is the internal cavity decay obtained in fig.1-b and  $\tau_i$

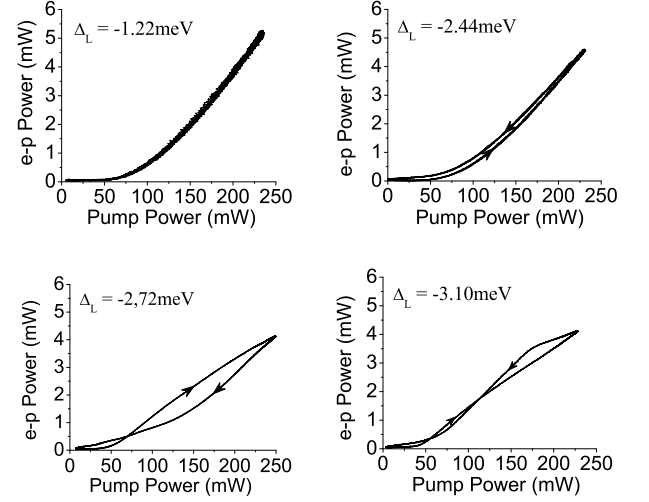


FIG. 3: Bistability sequence curves for a fixed cavity detuning ( $\Delta_c = -2.59\text{meV}$ ) and several pump laser detuning. The e-p power emission error is 3%.

is the cavity round trip time),  $L_{c(qw)}$  is cavity (quantum well) length,  $T = 8.5\%$  and  $R = 90\%$  are the cavity transmission and reflectance at resonance, respectively. For  $n_i = \tau_c/\tau_i \approx 400$  internal reflections (the cavity lifetime is  $\tau_c = Q/2\pi\nu_c \approx 0.38\text{ps}$ ),  $P_p \approx 70\text{mW}$ . But only a part of this excitation power is used to heat the sample ( $P_{therm}$ ); the rest is used to produce cavity photons ( $P_{ph}$ ), so that  $P_p = P_{therm} + P_{ph}$ . To obtain  $P_{therm}$  we analyze the e-p dispersion curve, finding  $P_{therm} = P_p(1 - E_{e-p}/E_L) = 170\mu\text{W}$ , where  $E_{e-p}$  and  $E_L$  are exciton-polariton peak emission and pump laser energies, respectively. Using the fact that each exciton is scattered by one-phonon to bottom of the LPB, we have  $N = P_{ph}\lambda_L\tau_{sp}/(hc)$  as the mean phonon number ( $\tau_{sp} = 3\text{ns}$  is the excitonic radiative spontaneous lifetime[17],  $hc/\lambda_L$  is the energy of each pumped photon laser). Thus, during time  $\tau_{th}$ , the temperature at the cavity can be raised by  $T = P_{therm}\tau_{th}/(NK) \approx 10\text{K}$ .

The excitonic effect provides a change of  $\Delta n_2/I = -0.005\text{cm}^2/\text{kW}$  and the thermal effect  $dn/dT = +0.0004\text{K}^{-1}$  (see Ref.[18]). Thus, in the first case, the changes in refractive index produce a deformation of  $\Delta L_{QW} = -2.8\text{\AA}$ , while in the second case the heating results in an expansion of the cavity, so that we have both a cavity refractive index change  $\Delta n$  (temperature-dispersive effect) and a cavity length change  $\Delta L$  (temperature-expansive effect), resulting in  $\Delta L_c = L\Delta n + n\Delta L = 10\text{\AA}$ . These results show that it is possible to observe a “backward” hysteresis due to thermal effects, because of the increase in cavity optical path with temperature, where the switch-down threshold intensity is higher than that for switch-up. When the pump power reaches its maximum, the entire cavity is heated, but the microcavity is already in the e-p laser regime, and the dispersive OB due to e-p population is predominant. This heating (some fraction of a microsecond later), affords a thermal-dispersive effect

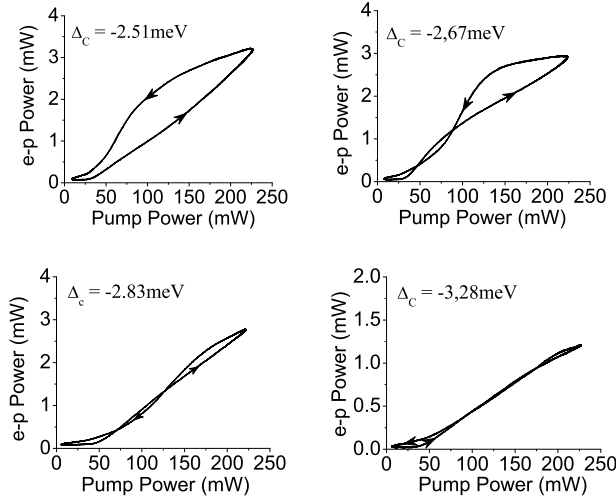


FIG. 4: Bistability sequence curves for a fixed laser energy ( $\Delta_L = -3.09 \text{ meV}$ ) and several cavity detuning. The e-p power emission error is 3%.

that achieves values, for the OB effect, greater than previously cited and the first crossing occurs. But, this effect is decreased because of the dissipation of the heat inasmuch as the pump power is reduced. Both heating and cooling processes occur above the e-p laser threshold, because the dissipation time is faster than the modulation of the pumping laser. Thus, as soon as the dissipation of heat is completed and a second crossing occurs.

Clearly, this thermal optical path-length mechanism is

not a second order process in the rigorous sense. That is, the index does not depend upon the instantaneous value of the intensity according to  $n = n_o + n_2 I$ , but rather on the time that the heat is dissipated by the sample. Moreover, the optical path length change depends on the total temperature variation, i.e., it depends on competition between absorption and heat conduction. Roughly speaking, it depends upon the energy absorbed during the last thermal conduction time. Thus, the variations in the refractive index is position-dependent, and should be weighted by the local optical intensity due to cavity resonance. These variations in the losses and/or in the absorption of the gain medium change the local heating of the cavity and the time to heat the lattice ( $\tau_{th}$ ) as even. In the fig.4 we can see a variation of this heat dissipation time for a fixed laser-exciton detuning, observing the curve-contour.

Summarizing, we find both single and double crossings in the OB curve due to a competition between the dispersive Kerr-like effect (caused by e-p population) and thermal effect, governed by the heat dissipation time. An analysis shows that the thermal dependence has a strong weight in the competition of the bistability effect, mainly due to temperature-dispersive effect. In spite of the temperature of the sample achieve  $\sim 20 \text{ K}$ , the system remains in the strong coupling regime, since reflectance measurements showed it at temperatures until  $40 \text{ K}$  [9].

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